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Key technologies of vertical take-off and landing infrastructure for urban air mobility: a comprehensive review

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Key words: Urban air mobility (UAM); Vertical take-off and landing (VTOL) infrastructures; Low-altitude operations; Communication, navigation, surveillance, and information (CNSI)

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Why a Review of VTOL Infrastructure Is Needed

- The large-scale development and practical implementation of urban air mobility (UAM) are confronted with numerous obstacles, among which is the inadequacy of vertical take-off and landing (VTOL) infrastructure.
- Key technologies for VTOL infrastructure are still in the early stages of development, and the government, industry, and academia have not yet reached a consensus on the standards for construction, management, and operation.

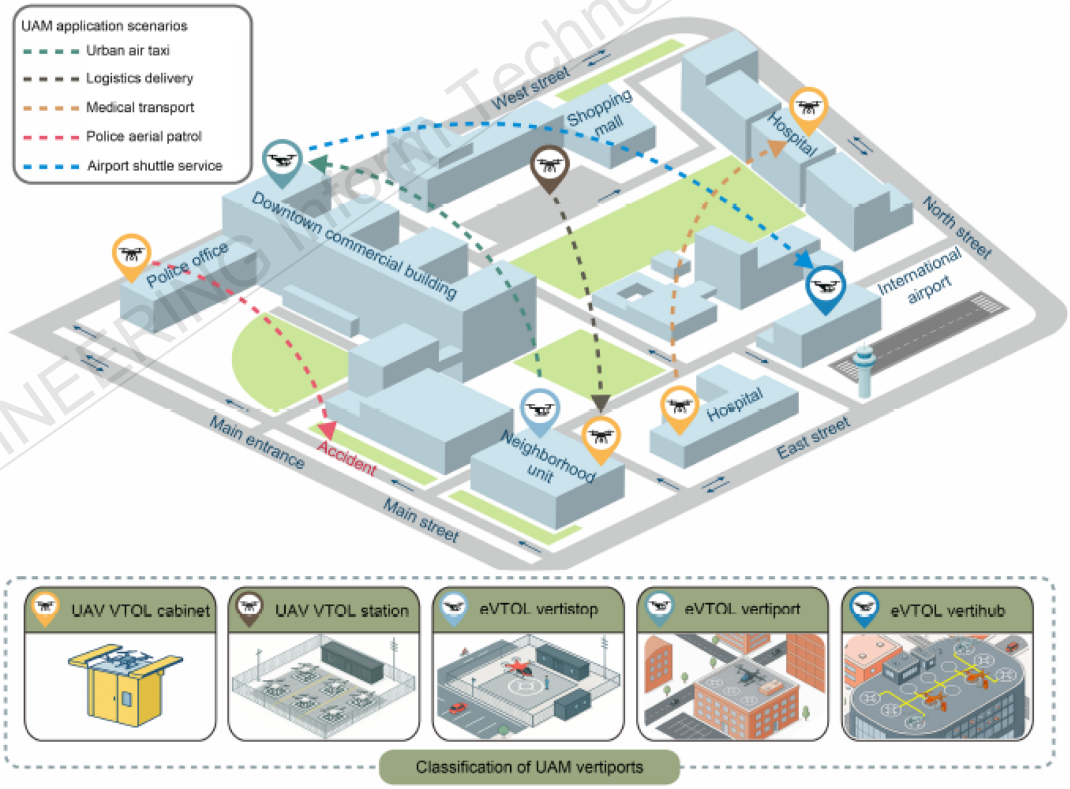


Fig. 1 Conceptual framework of the VTOL infrastructure for UAM

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What this review covers

- This review focuses on the various key technologies involved in VTOL infrastructure for unmanned aerial vehicles (UAVs) and electric vertical take-off and landing (eVTOL) aircraft, conducting an in-depth discussion from the following aspects:

- **Ground-side key technologies of VTOL infrastructure, including surface structure and layout design;**
- **Airspace-side key technologies of VTOL infrastructure, including obstacle clearance management, terminal airspace design, and air traffic management (ATM) and operational scheduling;**
- **Key technologies of communication, navigation, surveillance, and information (CNSI) services for VTOL infrastructure;**
- **Design of the public VTOL infrastructure.**

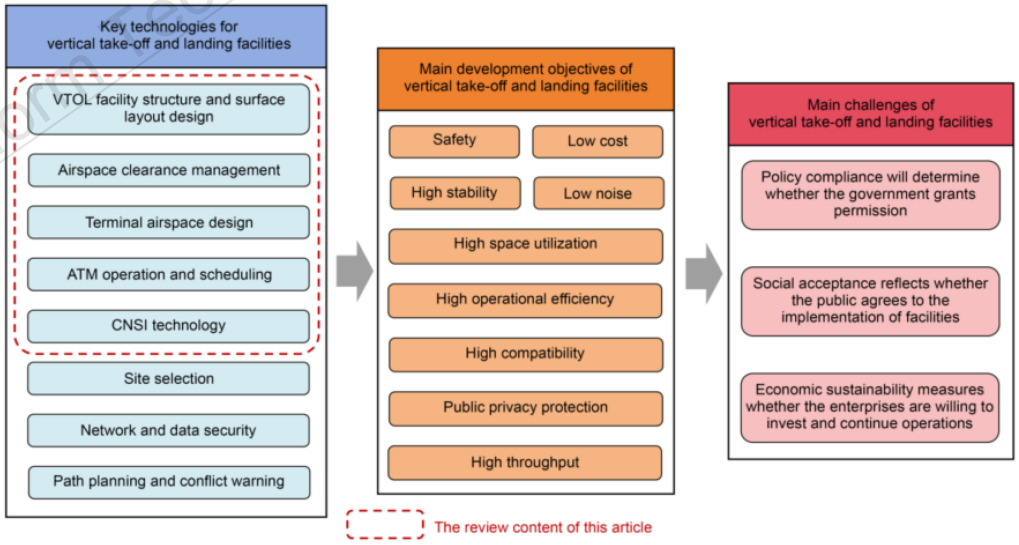


Fig. 2 Key technologies, development objectives, and current challenges for VTOL infrastructure in UAM

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Ground-side technologies for VTOL infrastructure

- Herein, ground-side technologies for VTOL infrastructure are examined from the complementary perspectives of structural and layout design. Structural design addresses the composition, dimensions, and physical parameters of the take-off and landing infrastructure structure, whereas layout design focuses on the spatial distribution and separation requirements of site functional zones. As eVTOL aircraft and UAVs markedly differ in performance, their ground side designs inevitably diverge. Given these differences, we outline the specific ground-side requirements and design features of VTOL infrastructure for eVTOL aircraft and UAVs.

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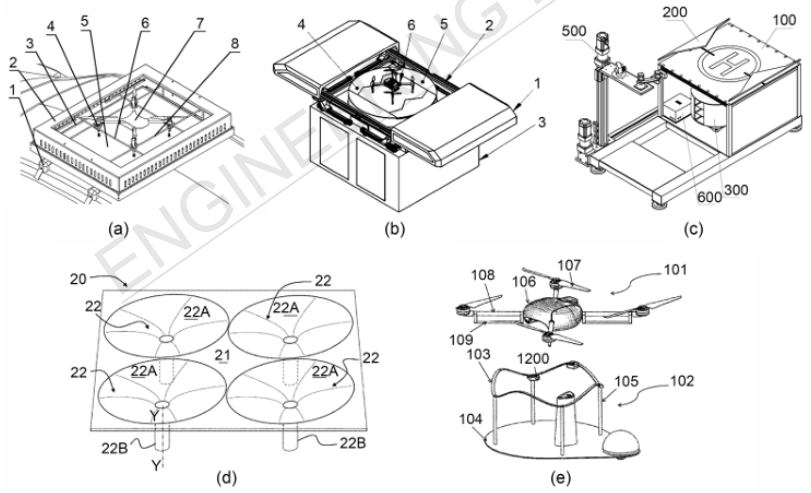


Fig. 5 Structural designs of positioning alignment systems for unmanned aerial vehicle (UAV) VTOL pads/cabinets. (a)–(c) illustrate the designs of three active positioning systems. (d) and (e) illustrate the designs of two passive positioning systems (Beijing Institute of Technology, 2017; Shandong University, 2017; Shanghai Yunxi Intelligent Systems Co., Ltd., 2017; Kespry Inc, 2018; Antonini et al., 2019)

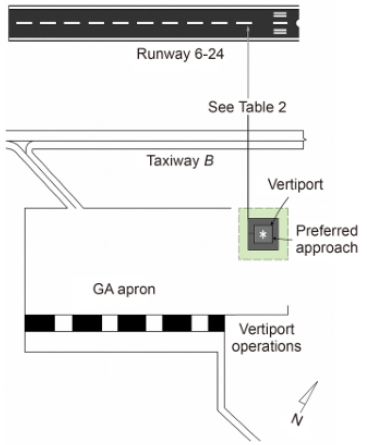


Fig. 7 Example of an eVTOL vertiport situated within an airport (Federal Aviation Administration, 2022). "GA apron" denotes the general aviation apron used for parking/servicing conventional (primarily fixed-wing) aircraft, in contrast to the eVTOL vertiport area

Airspace-side technologies for VTOL infrastructure

- Marked differences in size, noise, energy consumption, and avionics between eVTOL aircraft and UAVs lead to distinct requirements for terminal airspace architecture. However, their shared VTOL modes result in certain commonalities in arrival–departure trajectory planning, air-side obstacle restrictions, and operational sequencing. Accordingly, we analyze the common and differing aspects of eVTOL and UAV airspace-side technologies in light of their performance characteristics and discuss the technical requirements and optimization strategies for obstacle clearance management, terminal airspace design, and air traffic control scheduling.

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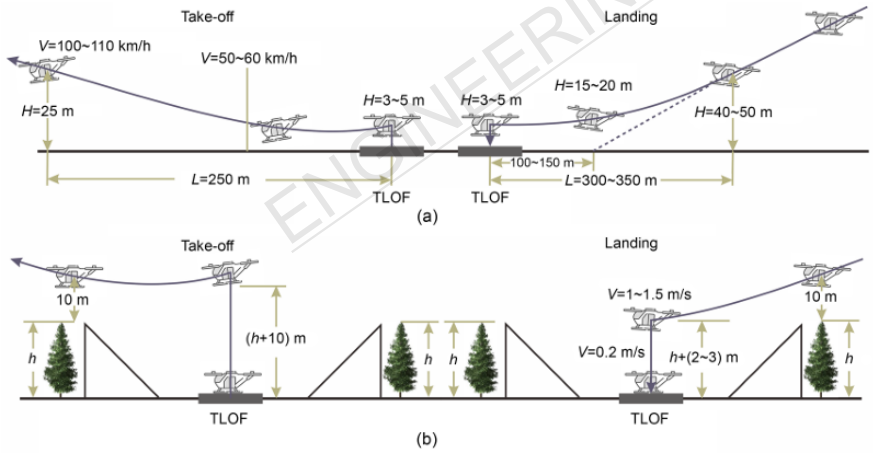


Fig. 8 Flight profiles for the two take-off and landing modes. (a) illustrates the flight mode of "tilted take-off and landing," while (b) illustrates the flight mode of "vertical take-off and landing"

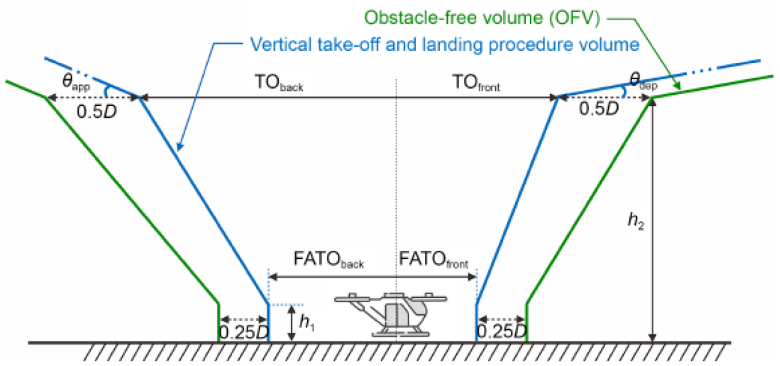


Fig. 10 Design method for the obstacle-free volume in the EASA standard

CNSI technologies for VTOL infrastructure

- Communication, navigation, and surveillance are indispensable for scheduling eVTOL aircraft and UAVs. Incorporating digital information services for the airspace surrounding a vertiport, this study proposes a CNSI architecture suited for low-altitude vertiport environments. It compares the technical requirements, characteristics, and existing challenges of CNSI infrastructure related to eVTOL aircraft and UAVs, and elaborates on the current development status and problems of various types of CNSI infrastructures.

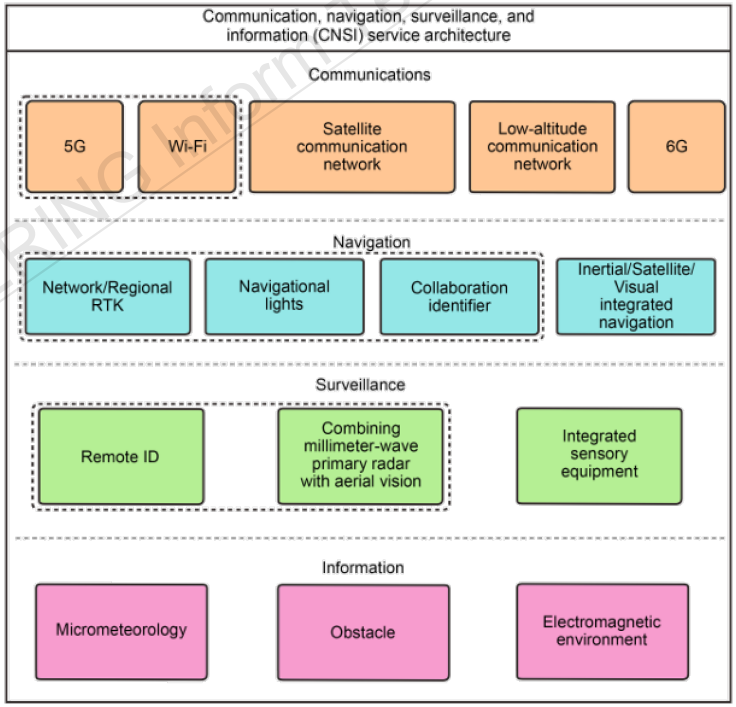


Fig. 11 Architecture of the CNSI services (dashed modules apply to UAVs; remaining modules apply to eVTOL aircraft)

Framework for public UAV VTOL infrastructure

- Combining the future multi-type, high-frequency, high-density, and high-complexity operational characteristics of UAM, this paper innovatively proposes a conceptual design framework for public UAV VTOL infrastructure for multi-operator scenarios. This framework can be mainly applied to public logistics hubs in commercial districts, supporting multiple logistics enterprises to share take-off and landing resources, avoid redundant construction, and provide a solution with both fairness and economy for the urban air mobility concept.

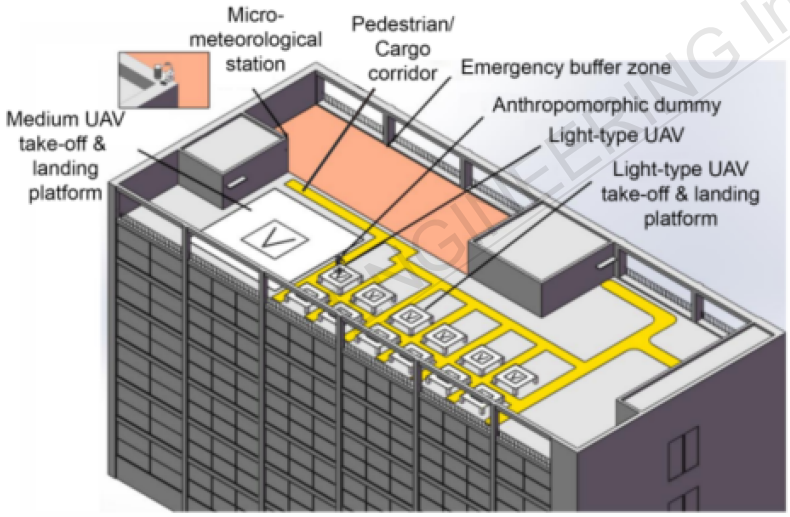


Fig. 12 Schematic layout of multitype UAV VTOL infrastructure incorporating an emergency landing zone

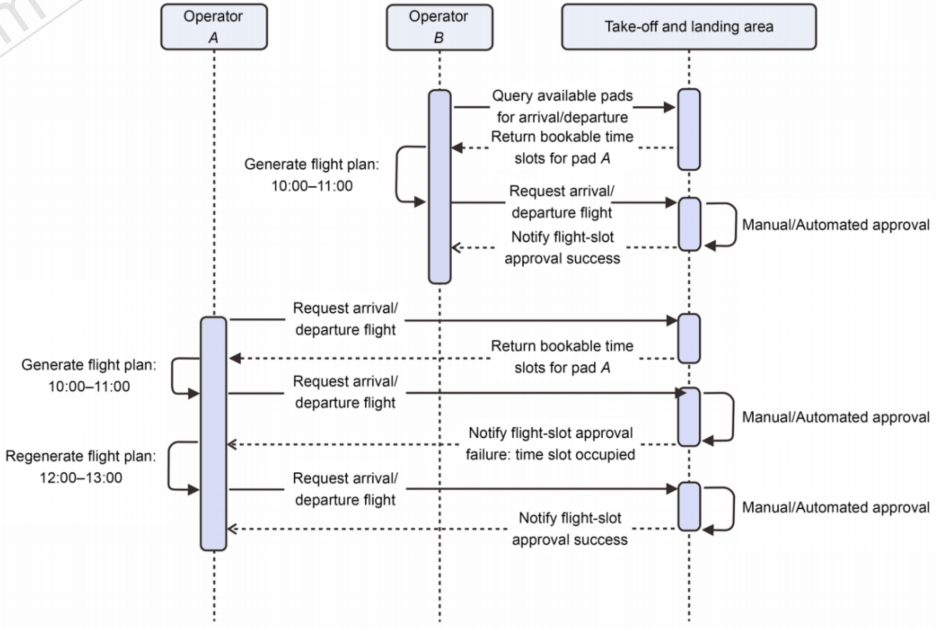


Fig. 16 Coordination workflow for multioperator arrivals and departures at the public UAV VTOL infrastructure

Future directions

Ground-side technologies

- Promote the International Civil Aviation Organization (ICAO) to issue unified standards promptly to avoid redundant costs from compatibility issues in manufacturing, certification, and operation;
- Research renovation schemes for eVTOL vertiports on old rooftops;
- Optimize UAV vertiport cabinet design and expand intermodal adaptation with ground unmanned vehicles;
- Promote multi-objective optimization of vertiport topology and supplement real-flight verification for functional area minimum spacing.

Air-side technologies

- Improve the obstacle limitation specifications for UAV VTOL infrastructure;
- Terminal airspace design should consider the partial unavailability of some areas caused by real-world complex scenarios;
- ATM operation and scheduling should focus on the multivehicle collaborative arrival and departure scenarios with multipad, multitype, and multioperator.

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Future directions

CNSI technologies

- For eVTOL infrastructure, future research must establish 3D low-altitude coverage and dynamic beamforming models, develop a robust integrity, continuity, and availability assessment framework suitable for urban multipath and electromagnetic interference environments, and model channel loading and collision probabilities for automatic dependent surveillance-broadcast (ADS-B) in high-density operations, while proposing corresponding congestion mitigation methods;
- For UAV VTOL infrastructure, research should focus on the joint optimization of energy consumption and reliability under urban near-ground occlusion constraints, and address the detectability and interface availability of remote identification (remote ID) in urban environments by establishing coverage models driven by receiver sensitivity, occlusion, and channel contention.

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Future directions

Integration of LLMs and UAM

- Large language models (LLMs) and UAM are increasingly synergistic, with preliminary achievements in technology, scenarios, and ecosystems. Driven by policies, core technology iteration, and growing public acceptance, LLMs' application in UAM is expected to expand to critical areas like vertiport scheduling and CNSI management, supporting UAM operational efficiency and safety and reshaping urban mobility.

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Conclusions

- This study systematically sorts out the research progress of key technologies for low-altitude vertiports in UAM from three dimensions: the land side, air side, and CNSI. On this basis, combined with the operational characteristics of multi-type aircraft and high-density operations, it innovatively proposes a design framework for public UAV vertiports for multiple operators, which includes apron layout design, terminal airspace design, and a coordinated operation architecture for multiple operators. We hope this study can help readers comprehensively understand the key points of various key technologies for vertiports and provide valuable insights and references for future research.

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Chenglong LI received his Bachelor's and Master's degrees in Navigation, Guidance, and Control from Zhejiang University and is pursuing his doctoral studies at Beihang University. He currently serves as Vice Dean and Associate Professor of the Flight Technology College at the Civil Aviation Flight University of China (CAFUC). He also acts as a member of the Safety Risk Management Working Group (WG-SRM) in Joint Authorities for Rulemaking on Unmanned Systems (JARUS).

As one of China's pioneering researchers dedicated to the research and advancement of advanced air mobility (AAM), his primary research interests focus on low-altitude operational safety and risk assessment, as well as the intelligent development of low-altitude aerial vehicles. Over the past three years, he has led his research team to undertake more than 10 research projects at the national, provincial, and ministerial levels, published over 40 academic papers, and secured more than 10 authorized invention patents.

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